

# Sun Patch Impact for the Evaluation of Operative Temperatures Distributions

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## Abstract

A numerical model has been developed in order to accurately simulate the transient thermal behavior of a building (a single room). This model has already been described in (Rodler et al., 2013): the energy balance equations consider irradiation, convection, air enthalpy and three-dimensional heat conduction. The particularity of the program is that it projects the sun patch on the inner walls. The operative and mean radiant temperature are important parameters for the evaluation of comfort indices. Their calculations require the air temperature values and the surfaces temperatures field which vary in the sunspace as a function of position and disposition of the person. We show the importance of the knowledge of the operative temperature distribution and its consequences on the thermal comfort. The refined 3D model is compared to the one obtained by the classical distribution of the solar radiation with a 1D conduction approach and by assuming all incoming radiation touches the floor. The sun patch impact and its three dimension effect are finally discussed for the comfort evaluation of a low inertia cell.

## Keywords

*Comfort; Low Thermal Mass Room; Three Dimensional Conduction; Sun Patch; Overheating; Operative Temperature*

## Introduction

In the context of zero net energy buildings, overheating affects generally internal comfort. This one has to be evaluated more accurately in the simulations taking into account a more precise surface temperature field. Generally, the simulation codes apply the solar radiation on the floor that gives for it a uniform temperature. In reality the solar sun patch conducts to high temperatures, locally, and affects, by radiation the comfort, depending on the body position. Thermal comfort is based mainly on six different parameters and can lead to complex studies (air temperature, radiation temperature, humidity, air speed, activity and clothing).

The air temperature, the radiant and operative temperature are important parameters for the thermal comfort description in buildings. The ISO 7730 is based on an analytical method for the evaluation of inside comfort relative to the PMV et PPD indices. This standard also considers local discomfort. According to this standard, in summer, for different types of uses of the room, the operative temperature should be maintained at  $24.5 \pm 1$  °C for an open space and  $24.5 \pm 2.5$  °C for a restaurant. The vertical differences of the operative temperature should not exceed 2°C for an open space and 4°C for a restaurant.

Comfort studies considering the radiation have already been realised but the majority of the thermal building codes consider an average value of radiant temperature ( $T_R$ ) which can not characterize correctly an environment from the thermal view point. Serres and Trombe (Serres L., 1997) (Trombe et al., 1999) studied the asymmetries of the radiant temperatures when considering two different solar heat fluxes. Thellier's (Thellier et al., 2008) work consisted in modelling the thermal comfort of an occupant in a glazed building. They showed that it required knowledge of several physical and physiological parameters. The study outlined the influence of the solar radiation. Gharbi and Boukhris (Boukhris et al., 2014) coupled a zonal model to an envelope model. They represented a south facing room with a window and analysed the impact of sun patch (or sunspot) on the air temperature distribution but unfortunately their heat conduction model is not 3D. La Genusa (La Genusa et al., 2005) developed a methodology to integrate solar direct radiation to the mean radiant evaluation but they didn't place the sun patch.

Here, an evaluation of the operative temperature distribution through the day is done for several points in the room considering the impact of sun patch.

## Theory

The three dimensional model coupling the geometrical sun patch model and the envelope model of the building has already been presented in past works (Rodler et al., 2013). Walls are discretised in control volumes but the air is modelled as a single air node and convection movements are not considered.

Contrary to other studies, we have integrated in the operative temperature ( $T_{op}$ ) the possibility of having radiation touching the spherical point studied in the room. The operative temperature is a uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. This temperature can be measured by a temperature sensor surrounded by a black sphere. The heat balance for this point can be written in the following way:

$$S\varepsilon\sigma(T_{op}^4 - T_{rad}^4) + Shc(T_{op} - T_{air}) + \alpha Et S_{app} = 0 \quad (1)$$

With  $E_t$  the radiation transmitted by the window which depends on the sun's incidence angle,  $S_{app}$  the projected surface of the sphere or apparent one touched by the sun,  $T_{rad}$  the radiant temperature,  $hc$  the convective coefficient between the sphere and the air,  $\varepsilon$  the emissivity of the sphere,  $\alpha$  the absorptivity of the sphere,  $\sigma$  the Stefan-Boltzmann constant and  $S$  the total surface of the sphere surrounded by the air.

Here the sphere's surface =  $4\pi(D/2)^2$ , the apparent surface of the sphere:  $\pi D^2/4$  and  $hc$  follows the correlation (Inard, 1988):

$$\left(1.14 + \frac{0.17}{D}\right) \Delta T^{0.25} \quad (2)$$

With  $\Delta T = T_{op} - T_{air}$

Finally we have:

$$\varepsilon\sigma(T_{op}^4 - T_{rad}^4) + hc(T_{op} - T_{air}) + \alpha Et/4 = 0 \quad (3)$$

The radiant temperature is calculated by considering a spherical point located at a spatial position in a room, and this point exchanges only by width wavelength radiation (infrared) with the envelope of the room. When it reaches the temperature equilibrium, that is to say, what it emits equal what it receives and absorbs, we call its temperature the radiant temperature:

$$T_{rad} = \sqrt[4]{\sum_{j=1}^N F_{0,j} T_{S,j}^4} \quad (4)$$

With  $F_{0,j}$  the diffuse view factor. We suppose to have only rectangular surfaces for the different envelope

components to consider, in the building thermal problems. The diffuse view factor between a spherical point and a rectangular surface can be easily calculated with the relation (5), according to the notations of FIG. 1.

The view factor between the mesh and the spherical point studied from the point of view of the point is calculated following these steps:

1. Projection of the mesh on a unit hemisphere centred on the point, obtaining a square ABCD
2. Area of the projection which corresponds to the view factor  $\omega$ : they are of the square projected is the sum of the triangles ABC and CDA given by

$$A_{ABCD} = A_{ABC} + A_{CDA}$$

Here  $A_{ABC}$  and  $A_{CDA}$  result from:

$$\tan^2\left(\frac{A_{ABC}}{4}\right) = \tan\left(\frac{s}{2}\right)\tan\left(\frac{s-AB}{2}\right)\tan\left(\frac{s-BC}{2}\right)\tan\left(\frac{s-CA}{2}\right) \quad (5)$$

heres =  $(AB + BC + CA)/2$

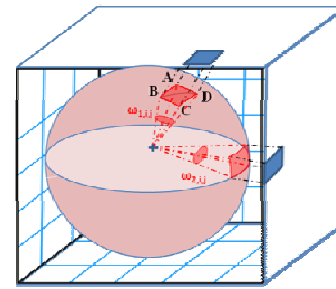


FIG.1 DIFFUSE VIEW FACTOR CALCULATION

## Input of the Model

The input data are the building characteristics and the meteorological measurements. Minute-wise weather data were used from the meteorological station of Vaulx-en-Velin, France (latitude: 45°46'43"N and longitude: 4°55'21"E, height 170m) (<http://idmp.entpe.fr/vaulx/mesfr.htm>).

## Case Study

We modelled a low thermal mass room ( $3 \times 3 \times 3 \text{ m}^3$ ) located in a building surrounded by different thermal conditions. This room is located on the upper floor with a south facing window. Its glazed surface is  $1.69 \text{ m}^2$ . Under the floor of the room we assumed air temperature to be kept constant around  $20^\circ \text{C}$ . The same was assumed for the lateral conditions unless for the south facing wall and the roof which are in contact with the outside air and receive solar radiation. The

lateral walls are made out of plaster, insulation and plaster; the southern wall has wood slab on the exterior and then insulation and finally plaster for the inside. The floor is made out of wood and insulation laying on a concrete slab. Finally the roof is insulated from the outside and inside is a plaster layer. The thermal characteristics of the materials are given below.

TABLE 1 MATERIALS' THERMAL CHARACTERISTICS

| Material   | Conductivity<br>W/(m.K) | Volumetric<br>heat capacity<br>J/( m <sup>3</sup> .K) |
|------------|-------------------------|-------------------------------------------------------|
| PLASTER    | 0.313                   | 0.65E6                                                |
| INSULATION | 0.037                   | 0.094E6                                               |
| WOOD       | 0.34                    | 1.26E6                                                |
| CONCRETE   | 1.75                    | 2.5E6                                                 |

The characteristics of the windows are known:

TABLE 2 GLOBAL CHARACTERISTICS OF THE WINDOW

|                   |        |
|-------------------|--------|
| Transmission      | 0.5400 |
| Reflection        | 0.2800 |
| Global absorption | 0.1900 |

## Results and Discussions

We simulated a week but focused on the 2<sup>nd</sup> and 3<sup>rd</sup> September 2012 where we have a day with clear sky conditions and another one with more diffuse radiation and fluctuations. We can see on the graph below that the global horizontal radiation (Gr) is mainly constituted by beam radiation (Br) and very low diffuse radiation (Dr) for the first day. High exterior bulb temperatures between 15°C in the morning and 27°C at midday are observed for these days.

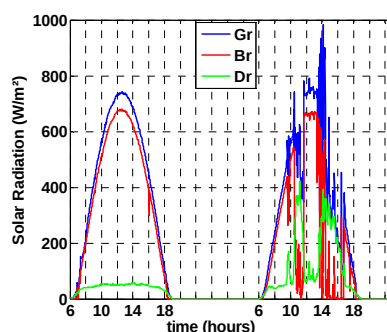
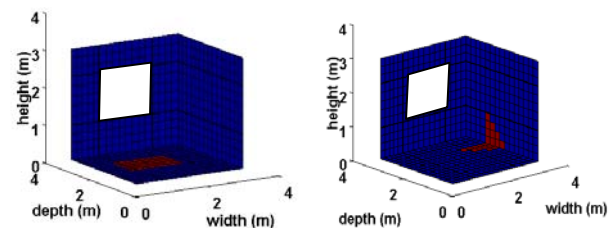


FIG. 2 SOLAR RADIATIONS

The figure below is a view from outside and bottom of the room meshed. The window is turned towards the south. The figure shows the front wall, the floor and the eastern wall. We can see that at 12h15 the sun patch impact (represented in red) is on the floor (FIG. 3) and at 15h30 it is on the floor

and the eastern wall. The surface of the sun patch through this day is between (FIG. 4) 0 and 1.4m<sup>2</sup> depending on the elevation of the sun in the sky.

Inside the cell we have 15 cells in depth, 14 in height and 19 in width; that is 3990 points where we calculated the operative temperature.

FIG. 3 SUN PATCH POSITION IN THE ROOM  
AT 12h15 AND 15h30

At 15h30, surfaces temperatures inside the room are between 28 and 46 °C which shows that the asymmetry of temperatures du to solar radiation is important. This has an impact on the operative temperatures which are between 31.5 °C and 28.5 °C, that is a difference of 3°C (FIG. 5 and 6) which can lead to discomfort. We can see that because of the sun patch, the temperatures are higher at the right (near the eastern wall) (FIG. 5) and the floor (FIG. 6) reaching 31.5 °C.

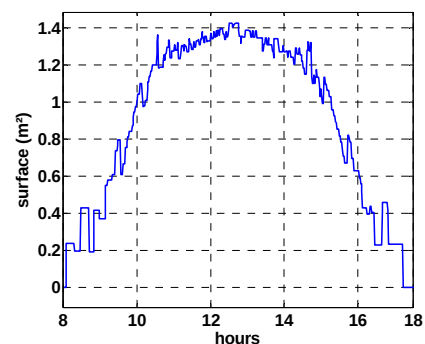
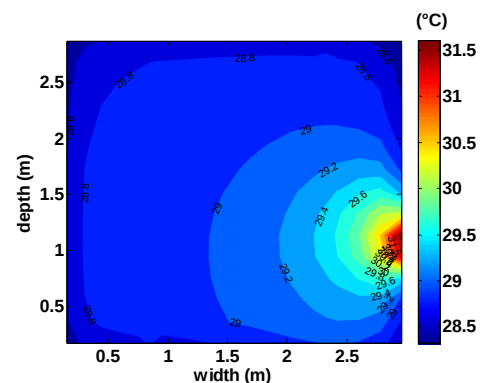


FIG. 4 SUN PATCH SURFACE EVOLUTION

FIG. 5 HORIZONTAL CROSS SECTION 50CM ABOVE THE  
GROUND AT 15h30

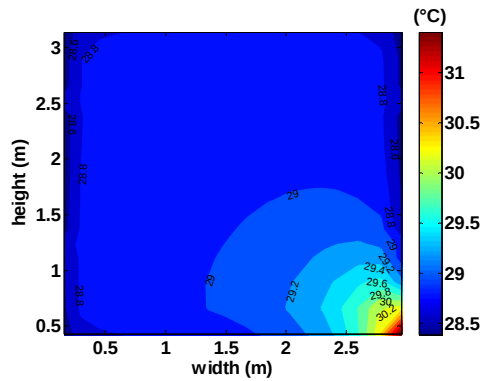


FIG. 6 VERTICAL CROSS SECTION 1M BEHIND THE WINDOW AT 15h30

We took the same model but considered only 1D heat exchanges across the walls. The incoming radiation was considered to reach only the floor but the amount of transmitted heat flow through the window is the same as for the previous study. All the other hypotheses and inputs are also the same as for the first case.

The main difference here is that the surface of the floor (9m<sup>2</sup>) is not equal to the surface of the sun patch as shown before. That is, the absorbed quantity of solar heat flux by the wall will be differently and consequently the heat exchanges between air node and surface temperature too. As already shown in a previous work (Rodler et al., 2013): when considering the sun patch, we usually tend to have lower air temperatures than when not considering it. The same is observed for the general tendency of the operative temperature (FIG. 7) of the middle of the room, reaching differences up to 1.8°C between the 3D (1) and the 1D model (2). We have also analysed the impact of having integrated the incident radiation on the black sphere. We compared the results with and without having the last term of the equation 3 considering only the 3D model. Here we can see that for this point (2m, 2m, 2m) that the operative temperature with the absorption of the solar radiation is higher (brown dotted curve) when the sun patch touches this point and differences up to 3.6 °C are observed between these results and when considering no radiation on the black sphere (blue curve).

Finally, we compared the results concerning the distribution of the operative temperature. At 12h15 we have operative temperatures between 26.7 °C and 27.4 °C with the 1D model whereas with the 3D we have temperatures between 26.6 °C and 28 °C. At 15h30 operative temperatures are between 28 °C and 31.5 °C for the 3D case and between 30.1 °C and 30.7 °C for the 1D (FIG. 8). At 12h15 the differences are

lower (up to 0.6°C) than in the afternoon where the differences can reach of 2.1 °C .

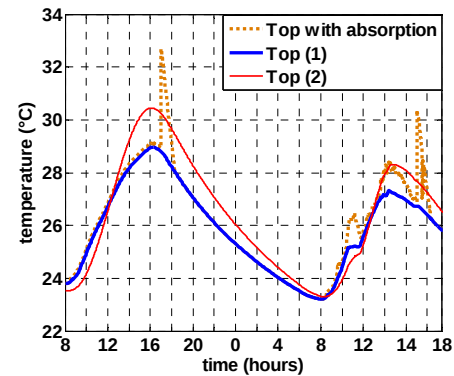


FIG. 7 SUN PATCH AND ABSORPTION IMPACT ON THE OPERATIVE TEMPERATURE

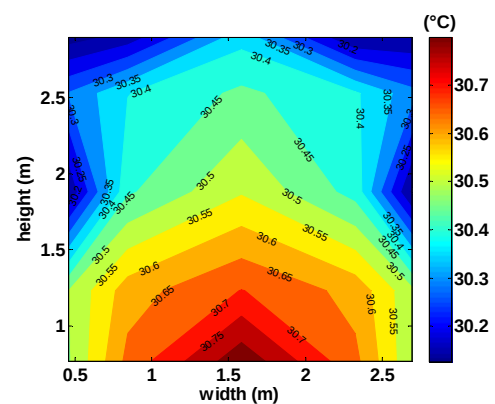


FIG. 8 VERTICAL CROSS SECTION 1M BEHIND THE WINDOW AT 15h30 FOR THE 1D CASE

## Conclusions

The majority of the thermal building codes consider an average value of radiant temperature (Trad) which can not characterize correctly an environment from the thermal view point. More detailed models are required when wanting to reach more accurate temperature fields and comfort considerations in the buildings. We have seen here by comparing two codes, that the sun patch evolution and its location have an impact on the operative temperature and its distribution. Contrary to other studies, we have integrated in the operative temperature (Top) the possibility of having radiation touching the spherical point studied in the room and have observed important differences up to 3.6 °C when the sun beam touches the spherical point. Differences between a simple approach (not considering sun patch and 3D heat transfers) and the detailed model could reach 2 °C. These differences could be more important for rooms or offices with large bay windows. Comfort criterion tends not to be anticipated well enough by too simple approaches neglecting solar radiation.

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